Renewable and Sustainable Energy Reviews 24 (2013) 557–565

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# An overview of fuel management in direct methanol fuel cells

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ARTICLE INFO

*Article history:*
Received 8 November 2012
Received in revised form
22 February 2013
Accepted 4 March 2013
Available online 28 April 2013

*Keywords:*
Direct methanol fuel cell
Flow-field design
Fuel delivery system
Fuel storage

ABSTRACT

Fuel cells were an important technology that could be used for a variety of power applications. The direct methanol fuel cell (DMFC) was a promising candidate for powering portable electronic devices such as laptops, digital cameras and cell phones. Compared with conventional batteries, DMFCs could provide a higher power density with a longer lifetime and almost instant recharging. However, many issues related to the design, fabrication and operation of miniaturised DMFC power systems remain unsolved. Fuel delivery was a key issue in determining the performance of a DMFC. To achieve the desired performance, an efficient fuel delivery system was required to provide an adequate amount of fuel for consumption and to remove the carbon dioxide generated in the fuel-cell devices. This paper presented a detailed description of various fuel flow-field designs for DMFCs and their respective advantages. This paper also discussed the current approaches and challenges in existing fuel delivery and fuel storage systems, including active and passive DMFCs and micro-fluidic systems. The commercialisation of DMFCs with storage was presented.



**Contents**



## 1. Introduction

The major issues involved in energy delivery systems include reducing costs and increasing reliability for commercial use. Fuel cells were currently being studied in most energy development fields as future green energy sources. Fuel cells offered stable power generation, transportation and traction to portable and micro-scale electronics. Several types of fuel cell with different potential applications and designs have been reported over the past 20 years [1,2]. Direct methanol fuel cells were prime candidates for portable applications due to their high-energy density, low pollution, rapid recharging and operation especially at room temperature. Fig. 1 provided a schematic diagram of a DMFC compartment.

Generally, reactions occurred at the anode and cathode in a DMFC to produce an overall reaction as follows:

$$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^- \quad (1)$$

$$1.5\ O_2 + 6H^+ + 6e^- \rightarrow 3H_2O \quad (2)$$

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1364-0321/$ - see front matter 
http://dx.doi.org/10.1016/j.rser.2013.03.013

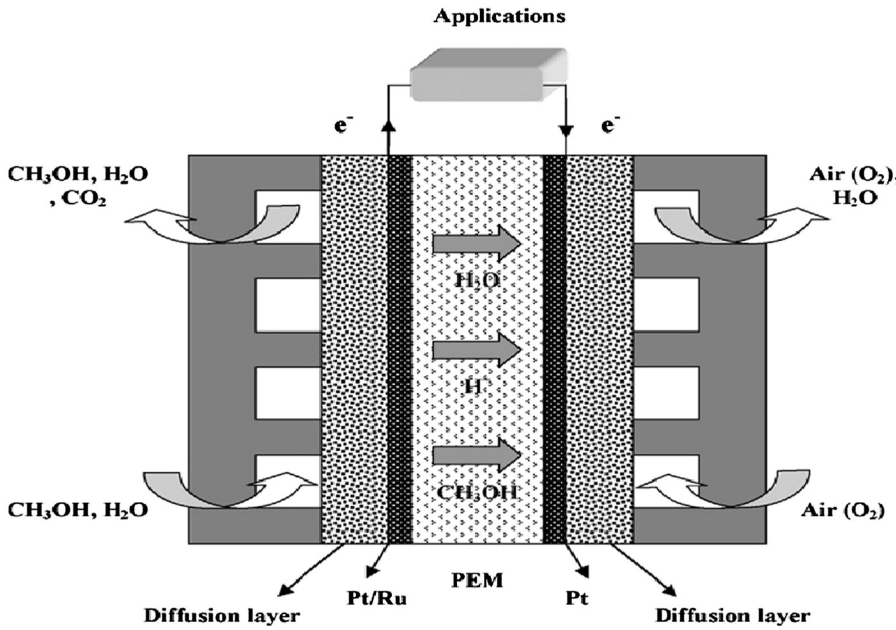


**Fig. 1.** Schematic diagram of DMFC [1].

$$CH_3OH + 1.5O_2 \rightarrow CO_2 + 2H_2O \tag{3}$$

Although a number of fuel-cell technologies were available for various applications, only those that permit near-room-temperature operation are suitable for portable electronics. Therefore, polymer electrolyte membrane fuel cells (PEMFCs) and direct methanol fuel cells (DMFCs), which could operate at temperatures below 80 °C, were a natural choice. The choice of fuel was also critical for commercial applications. Due to the storage, transportation and safety issues involved with hydrogen, fuel cells that used methanol as their fuel have recently attracted considerable attention. Methanol has the highest energy-to-carbon ratio of any saturated alcohol (equivalent weight 5.33) and is the only alcohol that can be completely oxidised in a PEMFC. These advantages of methanol were a good choice for alternative fuel applications. The benefits and challenges encountered in the development of DMFCs had been discussed in detail elsewhere [1–4]. Despite recent innovations, a number of issues must still be addressed before DMFCs can become commercially viable [5].

Many researchers, including Waidhas et al. [6] and Scott et al. [7], had discussed the benefits and challenges utilising a directly fuelled methanol system. To optimise a miniaturised DMFC power system, many engineering issues must be considered, including thermal management, methanol crossover [8], fuel delivery [9,10], oxidant supply and power conditioning [11]. Besides, other generally major technical concerns in commercialisation of DMFC are low cell voltage, current density and efficiency [12,13]. While in practical application, long start-up time and poor response to transient power demand are the problems [14]. However, this paper focuses on the technical feasibility of the fuel delivery system in DMFC. This paper provided a general overview of the fuel management in DMFCs, including flow-field designs and the advantages of efficient fuel distribution. This work also included a discussion of storage and delivery units for fluids and reviews the current challenges in this field.

## 2. Flow-field design

The flow field is the main compartment related to fuel management in a fuel cell. The functions of the flow field are to allow the fuel to flow continuously in a uniform distribution to reach the surface of the membrane electrode assembly (MEA) efficiently and to provide an improved removal of carbon dioxide from the cell [15]. The removal of the $CO_2$ produced in the overall reaction is critical because $CO_2$ can degrade the DMFC performance and damage the overall system if not managed properly [16–18].

Several flow-field designs had been developed based on conventional serpentine flow fields or single-serpentine flow fields (SSFFs) such as the parallel flow field [19], the convection-enhanced serpentine flow field (CESFF) [17,20], the multi-serpentine flow field (MSFF) [21] and the mixed parallel/serpentine flow field (MFF) [22] and interdigitised flow field (IFF) [23]. The DMFCs exhibit improved performance over conventional fuel cells. The advance flow fields could potentially reduce methanol crossover, increase fuel utilisation, mass transport and membrane humidification and improve voltage and current output.

From design perspective, the one-input four-output design demonstrates improved $CO_2$ and water removal than the one-input one-output design [24]. In fact, $CO_2$ bubble evolution has a detrimental effect in small flow channels due to elongated gas-slug blockage [25]. The existence of elongated gas slug is most prevalent at high current densities. In addition, changing other parameters could help to solve the $CO_2$ issues such as increasing the open ratio, the depth of length, the channel width, and positioning the cell vertically rather than horizontally [26,27].

Computational fluid dynamic (CFD) was applied to the flow-field design to investigate the effects of flow-field structures on DMFC performance for the four different flow designs [28]. The simulation results and experimental work demonstrated that the double-serpentine flow field had the most effective flow velocity distribution and the most uniform temperature distribution for the best DMFC performance. The experiments of Krewer et al. [29] suggested reduced models of ideal networks could determine the influence of both steady-state and dynamic DMFC models as shown in Fig. 2. Danilov et al. [30] developed an improved two-phase model with a new sub-model and an improved three-dimensional CFD model that included all relevant phenomena and was valuable for designing a DMFC with improved gas management. The CFD could help to solve many flow-field issues and could enhance DMFC performance by leading to the discovery of a good flow-field design.

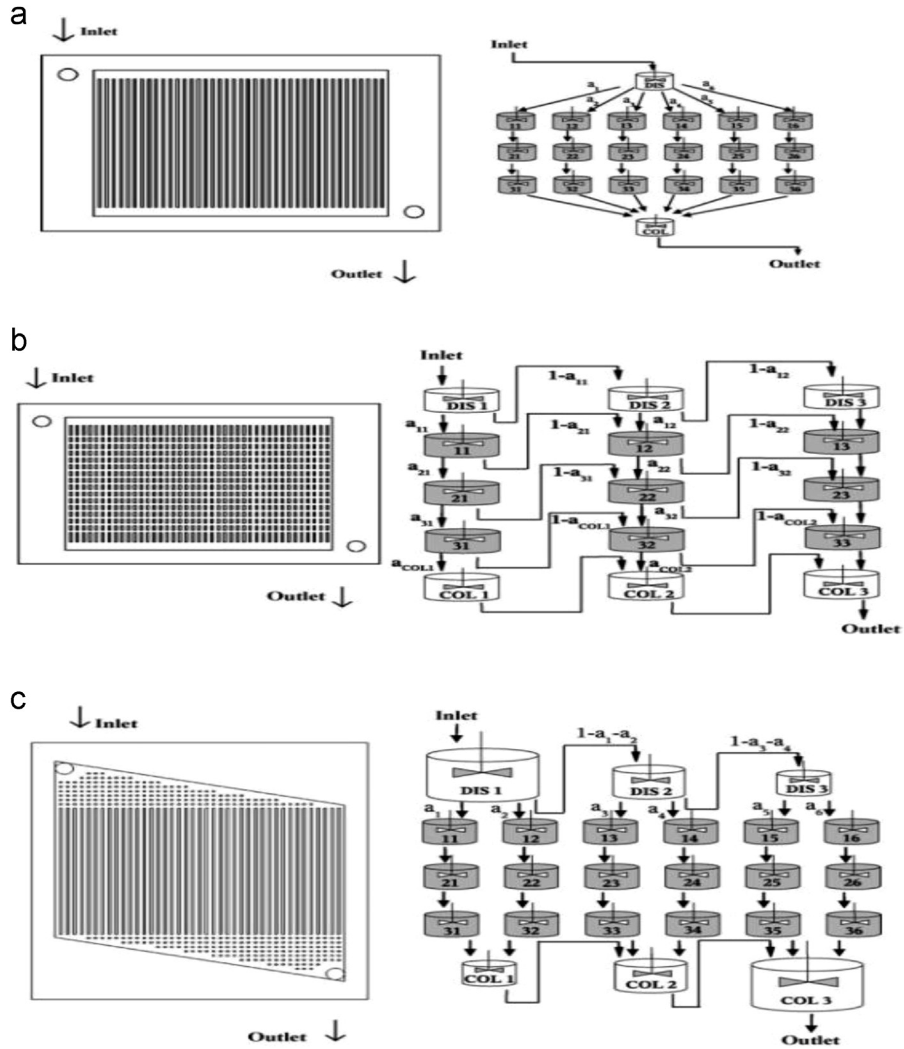


**Fig. 2.** Flow fluid design correspondent to CSTR network models [29]. (a) Parallel channel design geometry, (b) Spot design flow field (left) and (c) Rhomboidal design flow field (l.h.s.).

## 3. Existing approaches to the fuel delivery system

Fuel delivery systems can be divided into three categories: active, passive and semi-passive depending on their method of fuel and oxidant supply. An active system requires moving parts such as a pump or fan to feed fuel and oxygen into the fuel-cell stack, while a passive system supplies fuel without requiring external parts. Passive systems feed the fuel using the theory of concentration gradient, the natural convection capillary force and gravity [31]. The third category, semi-passive systems, combines active and passive systems. Passive and semi-passive systems are generally chosen for their compactness, simplicity and reliability for portable applications requiring power below 10 W [3]. In micro-fluidic DMFC systems, micro-electromechanical systems (MEMs) are used as a fuel delivery system. The major difference between micro-fluidic and conventional DMFCs concerns the size; controlling the flow and other parameters in a very small device is quite challenging. These MEMs basically include both active and passive systems.

### 3.1. Active fuel delivery

The literature records several developments in active fuel delivery systems for DMFCs. Xie et al. [32] at Motorola Labs presented the active fuel delivery system presented in Fig. 3 in which methanol cartridges provide fuel to restore the system. More independent storage is required to compete with batteries as common power sources for today's portable devices. Some progress has been made toward this goal using micro-reservoir arrays [33,34], bipolar plates [35], or printed-circuit-board (PCB) technology [36].

In micro-fluidics, a micro-fluidic pump drives the system circulation. The pump's power consumption is critical, especially for portable applications [37–39]. Thus, research attention has been focussed on maximising the fluid storage volume and power efficiency, although some research has generated new ideas for extending the performance of active systems using a thermo-pneumatic micro-pump with a corrugated diaphragm [40], a Lorentz force micro-pump [41], or linear and rotary actuation pumps [42], respectively, a capillary pump or a piezoelectric valve-less micro-pump. With various recent developments in micro-fuel cells, demand for these devices has increased. Several companies have focused on micro-fuel cells such as Toshiba, Samsung, Motorola, NEC, Manhattan Scientifics Inc., MTI MicroFuel Cells Inc., Neah Power Systems Inc. and PolyFuel [43].

MTI Micro has made advancements in internally transferring the water produced by the reaction at the cathode to the anode without using any conventional pump. Fig. 4 presents (a) an active DMFC system [44] and (b) two schematics of typical DMFC systems and a schematic of the MTI Micro Mobion® Technology. The water recycled

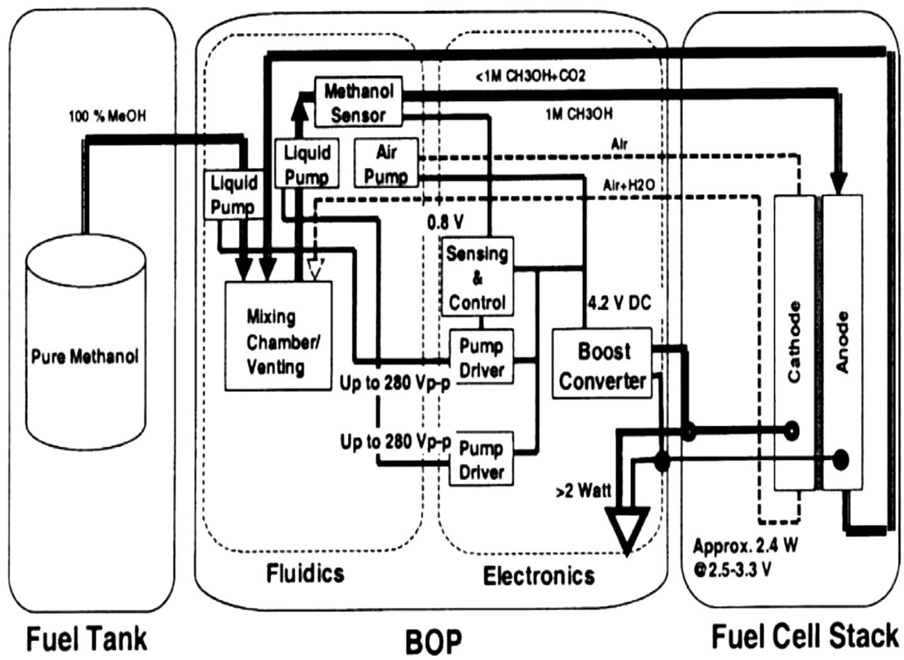


**Fig. 3.** Active type fuel delivery in Motorola Lab [35].

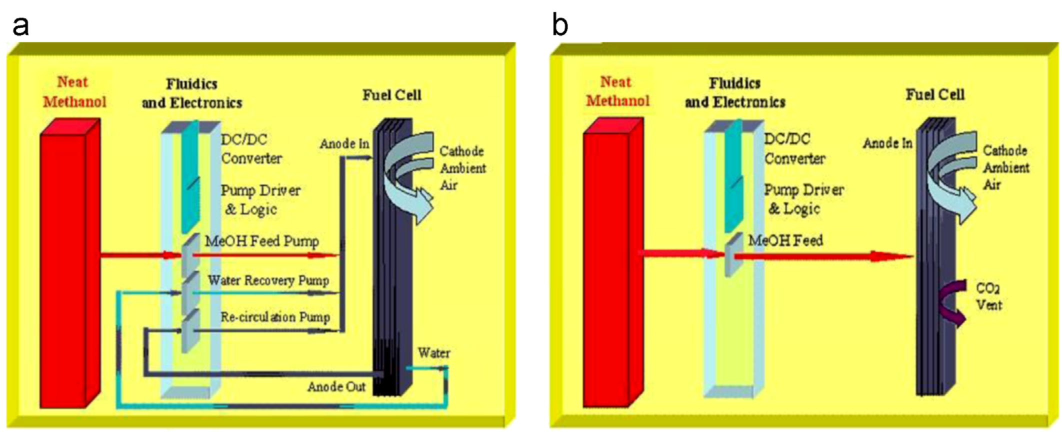


**Fig. 4.** MTI Micro's Mobion Low Energy Content DMFC [44]. (a) Active system and (b) passive system.

from the reaction was not wasted after the process, so no waste reservoir is needed to collect the water. From a practical standpoint, no wastewater was generated that could carry other side-reaction products, which might endanger the user. Guo and Cao [9] invented a capillary pump using a wicking material between the methanol and water reservoirs. The wick is made of a water-resistant layer to prevent water from backflow. A pinch valve in the middle of the wick controlled the flow rates. The methanol dilutes in the water continuously at a certain rate. The problem with this method was uncertainty of methanol concentration that fluctuated the performance. Piezoelectricity was another potential technology for portable applications. This technology had been utilised to improve fuel cells by Zhang and Wang [45]. Piezoelectricity could convert reciprocating movement to create an effective pump for micro-fluidic applications as shown in Fig. 5.

### 3.2. Passive delivery

Simple devices that did not consume energy were much more reliable than high-energy pumps when operated for small volumes at low current densities. Passive delivery had the advantage of independently reserving electricity to operate the system, to meet fuel-cell objective of producing electricity without connecting to a power supply, and it had some flexibility features. In passive delivery system several technical parameters need to be considered such as methanol concentration, cell orientation, current collector, MEA design and also operating conditions [27]. Furthermore, stacking effect was different from single cell. It is essential to gain deep insight on those parameters study with passive supply reactants (Table 3).

Kim et al. [46] developed high-performance single cells and monopolar stacks of micro-DMFCs under passive-feed conditions. Gottesfeld et al. [47] described a DMFC system with two features: on-board neat methanol and water recycling by which effluent gases ($CO_2$) are used to drive fluids between the elements of the fuel-cell system. Han and Park [48] presented a DMFC that incorporated a small back-up battery with the fuel cartridge installed atop the hybrid power module. Yang and Ling [49] demonstrated a passive fuel delivery system integrating their laboratory findings into a prototype driven by surface tension with power-free fuel delivery. Gao and Faghri [50] and Shibasaki et al. [51] presented a new miniature passive DMFC based on capillary action that controls the liquid

movement in porous media. Ye and Zhao [52] demonstrated a passive fuel delivery system for DMFCs that utilises a natural circulation mechanism. Chan et al. [53] had proposed a new self-regulated passive fuel-feed system that not only enables a passive DMFC to operate with highly concentrated methanol and without serious methanol crossover but also allows the self-regulation of the methanol feed rate in response to a discharging current. Zhu et al. [54] demonstrated a fuel delivery system based on gravitational force, while Meng and Kim [55] presented a new passive DMFC combining both gravity and capillary movement. Table 1 summarises the characterisation, advantages and disadvantages of passive fuel delivery systems.

### 3.3. Semi-passive fuel delivery

Fig. 6 shows the semi-passive design proposed by Li et al. [56]. Semi-passive DMFC delivery led to another development that could enhance DMFC performance: using an active system to increase the oxygen supply could enhance the overall reaction and reduce the intermediate products that could harm the electrode.

## 4. Current problems and advances in storage systems

### 4.1. Active systems problem

For active systems, external components such as pumps and valves facilitate the fluid flow and control. However, for such a small power output, the use of pumps and valves in DMFCs consumes a great deal of money and energy. In terms of design, these components also occupy larger spaces than the DMFC size itself, which is especially important for portable applications. Pumps required a maintenance schedule that could be burdensome. In a worst-case scenario, a broken pump could be be hazardous and create sparks that could ignite the methanol thus damaging the system. Pumps also limit how low the flow rate can be. Those auxiliary compartments of active systems were included in balance of plant (BOP) that needs to consider effectively [14,57].

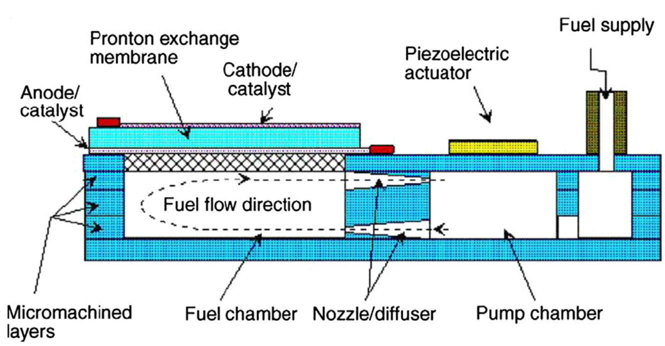


**Fig. 5.** Schematic of the miniaturized DMFC system driven by piezoelectric valve-less micro-pump [45].

To reduce complexity of active system, process integration might be helpful as suggested by Zenith et al. [58]. The integrated system design depicted the superior system could be possibly engineered. It managed to reduce size and weight of the system. But it apparently had disadvantages in increasing loss unreacted methanol at the exhaust. This system was reported better for portable application due to small size and less weight.

### 4.2. Passive system problem

Passive system storage was simple, lightweight and easy to fabricate; without any external parts it was more reliable for portable applications. Conventionally, passive system DMFC was fuelled manually by syringe for certain volume depends on the anode storage design. Due to the limitation of volume of passive system, passive DMFC needs to be refill after another to sustain electric supply. It consumes time to refill. In addition, storage organisation should be concern to prevent any leakage, which could be unhygienic and expose users to methanol toxins. Thus, open tank also not permissible for high concentration in terms of safety.

In passive, it was important to maintain appropriate methanol concentration in order to maintain the performance [59]. A review by Zhao et al. [27] on passive DMFC concluded passive DMFC was significantly different from active system. The difference of passive and active DMFC led to different applications. The highlights were suggested: (1) design of fuel supply system, anode current collector, anode diffusion layer and orientation independent operation of fuel cell play important aspects in mass transport at anode. (2) While at the cathode, the issues were related to enhance oxygen supply and water removal management. (3) Reducing heat dissipation from the cell. Nevertheless, passive system was challenging to maintain the concentration as well as the performance.

$CO_2$ generation in passive DMFC was good for pressure increment and also temperature in the cell that help to improve the performance. It also affected by concentration of methanol and MEA design itself. At high concentration of fuel and high current density, $CO_2$ production was crucial. The bubbles were accumulated in long gas slug especially at high concentration and current density which gave problem of $CO_2$ removal. The high flow rate was important to push out the $CO_2$ before it took side to create a layer between anode of

**Table 1**
Summary of flow-field design.

| Design by | Flow-field design | Advantages/disadvantages |
|---|---|---|
| Wu et al. [79] | Micro-fluidic structured consisted plural micro two-phase counter-flow. Capillary force assisted the transportation of the fuel and also $CO_2$ | – Enables the formation of liquid–gas meniscus |
| Padhy and Reddy [80] | Bipolar plated provided barrier layer between methanol and anode. Help reducing methanol crossover and $CO_2$ release | – Stack efficiency increased to 51%<br>– Low permeability<br>– Reduce machining costs |
| Xu et al. [81] | Two parallel flow-channel separated by gap<br>– Upper plate-grooved serpentine flow channel<br>– Lower plate-serpentine flow channel | – Could operate up to 16.0 M of methanol |
| Baglio et al. [82] | Two designs were proposed:<br>(1) Plastic plates coated by thin-gold-film current collectors<br>(2) Thin gold film deposited on external borders of the fuel and oxidant apertures | Design two better mass transport and longer operating hour Design one higher OCV and stack voltages at low current levels |

**Table 2**
Summary of passive type delivery DMFC.

| Design by | Prototype/concept | Advantages/disadvantages |
|---|---|---|
| Shimizu et al. [83] | Convection was main concept of transportation for air-breathing DMFC. Air-breathing DMFC simplified the DMFC without using air pump to fuel the oxygen at cathode side. However, air-breathing DMFC significantly applied for lower performance which suitable for portable device | – Simple and good for small volume |
| Kim et al. [46] | Monopolar stack of micro-DMFC<br>– Anode side-plate contained channels and large open spaces for storage of methanol solution | – Simple, easy made and user-friendly<br>– limited volume can supply for one time |
| Gottesfield et al. [47] | On- board methanol and water DMFC | – Simple and small<br>– Only can be applied for fixed volume<br>– Fuel fully consumed |
| Han and Park [48] | Cartridge<br>– GRAVITY mechanism | – User-friendly and portable<br>– Battery for back-up electricity increased total energy utilises |
| Yang and Ling [49] | Surface tension driven fuel capillary<br>– Methanol and water separated by a membrane made of PTFE (polytetrafluoroethylene) | – Separated chamber useful to maintain methanol concentration from degradation<br>– Small and portable<br>– Exposed of methanol to environment is dangerous<br>– Recycle water produces from reaction<br>– Only can supply methanol for certain time with limited volume |
| Faghri and Guo [51] | Capillary phenomenon | – Small and portable |
| Ye and Zhao [52] | Gravity mechanism<br>– Different of height creates pressure drop to flow the fuel from the storage to the anode<br>– The $CO_2$ production creates an upward force to move the fuel to the storage from anode side of DMFC | – Natural circulation<br>– No need external pump to move the flow<br>– Feed flow rate increase, current density increase<br>– Storage consumes a lot of space depends on fuel utilisation |
| Chan et al. [53] | Gravity mechanism | – Self-regulated<br>– The flow rate depends on height and diameter of tube<br>– Using relief valve to control $CO_2$ |
| Yingli Zhu [54] | Gravity mechanism | – Simple<br>– Could supply various concentration of methanol<br>– $CO_2$ removal provided<br>– Flow rates depend on methanol concentration, inlet and outlet tube diameter and total volume |
| Shibasaki et al. [51] | Capillary phenomenon<br>– Using filter paper with slits | – Filter paper with slit improved the fuel-feed supply compared using filter paper alone<br>– Filter paper tends to soak that will cause the fuel delivery could not sustain for a long time |
| Meng and Kim [55] | Combination of gravity, capillary action | – Small, portable and easy made<br>– Self-recirculation of fuel<br>– Self-breathing to remove $CO_2$ |

MEA and methanol which return low permeability of methanol pass through the MEA. For passive DMFC which low flow rate was applied was recommended to take a note on $CO_2$ transportation [60]. Otherwise, thicker methanol barrier needs to be applied that currently reported decrease methanol crossover, increase fuel efficiency, and improve the performance [61].

## 5. Commercialisation of DMFC

Commercialisation of DMFCs would mark a great advance in the portable application market. Recent findings indicate that portable fuel cells had great promise for the future but not immediate commercialisation because current focus was on competition with other technologies [62]. The Toshiba mobile fuel-cell "Dynario (Dinario)" was one example of a DMFC product. Toshiba had been building DMFCs from 2002 until 2010 as reported. Several DMFC models have been commercialised since then [63]. Fig. 7 shows the Dynario with its fuel-cell cartridge. The method of fuelling this DMFC involved manually pressing the bottle of methanol into the storage compartment built into the stack. It took 20 min to fill up the cell with methanol. The DMFC stack resembled an active system that uses a pump and valves to move the fuel. The tank capacity was approximately 15 ml, while the provided cartridge contains 50 ml of highly concentrated methanol. The expected power output is DC 5 V, 400 mA. The DMFC offers the flexibility of recharging anytime and anywhere; however, the cartridges was sold separately. The cost of the device is about $328 while the cartridge is about $0.03 [64].

SFC fuel cell is one of the companies who applied methanol fuel cell for portable and big application such vehicles and power supply. The cost of their product, EFOY Pro Fuel Cell (600, 1600, 2200, 2200XT) is about £2496.00–£6673.00 varies by its capacity. The power output ranged from 25 to 90 W. The volume also varies

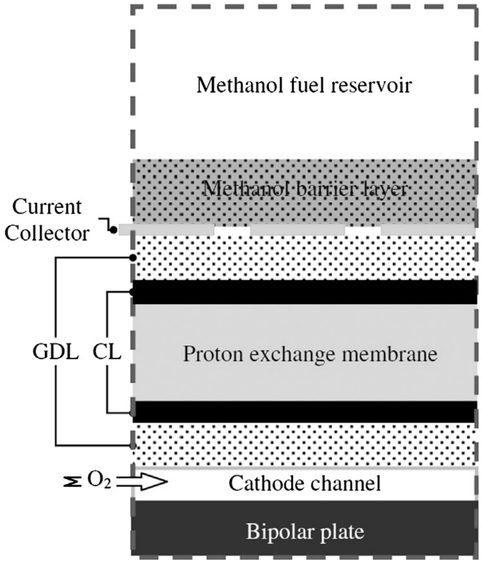


**Fig. 6.** Semi-passive DMFC [56].

**Fig. 7.** Toshiba mobile fuel-cell “Dynario (Dinario)” [64].

from 5 to 28 L depends on the series which also provided at cost £27 per litre. DMFC of SFC fuel cell mostly used active system. SFC fuel cell also developed other DMFC for military and industrial instead of consumer product [65].

Fig. 8 shows DMFC compartment with a cartridge made for mobile applications. The article was published online in 2004. The commercialisation of this type of mobile fuel cell had opened some doors for additional DMFC use. In 2008, PolyFuel developed a DMFC integrated with a Lenovo T40 ThinkPad computer with a swappable cartridge [66,67]. This active DMFC system with a battery back-up had been used to power a humanoid robot. The robot, whose name was HUBO, was an example of a battery/DMFC hybrid power system. The power output is approximately 42 W with a net electric power efficiency of 22.0% [68]. This major accomplishment of a hybridised DMFC system obviously provided a new perspective to the DMFC field. The problems of methanol crossover and water flooding related to the fuel management system encouraged the development of a high-concentration methanol DMFC. Table 2 shows some DMFC prototypes using high methanol concentration that had been developed. High-concentration methanol affected the MEA, especially the membrane portion. The MEA was specially designed to support high-concentration methanol, water recovery, water removal and an adequate flow rate of methanol and oxygen. Passive delivery systems provided good potential, as suggested previously [69].

It is observed that most of the researchers obviously are more interested in passive delivery system DMFC compared to active system. However for commercialisation, most of the DMFCs were integrated with active system. The situation could make us believe the active system is compatible in commercials way. It was true the active system provided better flow, temperature, humidity control compared to passive system. The parameters also affect the performance of DMFC which major concern for any developer fuel-cell active system. It was no regret to say active DMFC was promised product that compatible in any situation. Besides DMFC and battery are competing to each other's which give the best service. Compared to battery, active DMFC consumes more energy than electricity supply. Moreover, the cost of active DMFC is quite high to fulfil customers' satisfaction. Due to that, the passive system development study is an option for DMFC in future to be great choice that offers naturally fuel supply for portable application.

Furthermore, the market of DMFC of today is not same as in 2005–2006 environments where a lot of DMFC research patents reach their peak most in the world. The atmosphere at that timeframe, to the developer wish to aim their commercialisation product around 4–5 years later but unfortunately the expected outcome, was not a big favour [70,71]. The opportunities to put DMFC on the track again by doing some magic of sciences application in passive DMFC that have equal performance as active system that also reduce the cost and energy consumed like what had been done by Yang and Liang [49]. However, most of the passive system studies focus on single DMFC rather than multiple stacks where maybe it could be advantage of passive system to compete with active system DMFC and other fuel cells.

## 6. Future research and developments

DMFC now can be easily found as finished electronic product. In 2006, it was reported 6000 portable devices based on DMFC system were produced [72]. As DMFC market grown up, restriction such reliability, cost, noise, efficiency and regulations is same like other existing power system. With the fast changing multi-function portable electronic devices that require more energy sources become a problem for DMFC to keep up with the pace. In addition, consumers power could not be neglected as well who are pointing at the cost, convenience and physical size of potential young technology like DMFC could offer better life [27,73].

The cartridge plays main role to supply methanol and run DMFC. The size of cartridge also determines the running time of DMFC. Furthermore, the toxicity of high concentration of methanol and other by-products also needs to be aware. Safety issues regarding to methanol fuel storage made developer concern with

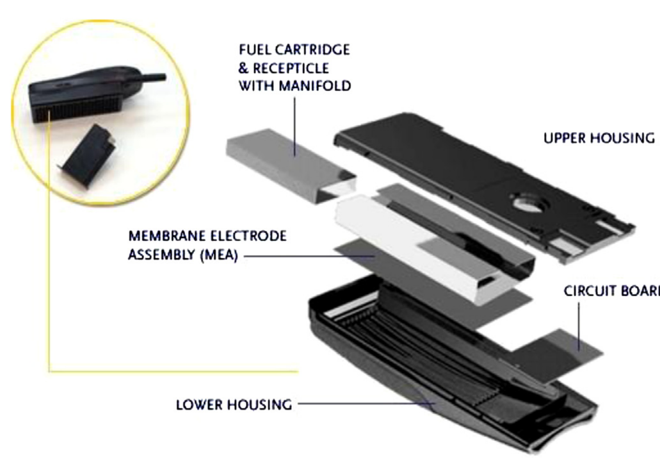


**Fig. 8.** Honeycombed membrane of DMFC from Polyfuel [66].

**Table 3**
Technical specifications of some DMFC prototypes [69].

| Company | Application (power) | System volume-based energy | Fuel volume-based energy | Conversion efficiency (%) |
|---|---|---|---|---|
| Motorola Lab | Charger (1 W) | 77 Wh $L^{-1}$ (62 h with 100-cc methanol) | ~620 Wh $L^{-1}$ | ~13 |
| | Charger (2 W) | 155 Wh $L^{-1}$ (48 h with 200-cc methanol) | ~956 Wh $L^{-1}$ | ~20 |
| PolyFuel Inc. | Laptop computer (15 W) | 325 Wh $L^{-1}$ (10 h on a single fuelling) | | |
| MTI Micro Fuel Cells Inc. | Charger (1 W) | | ~1800 Wh $kg^{-1}$<br>~1420 Wh $L^{-1}$ | ~29 |
| LG Chem | Laptop computer (25 W) | ~250 Wh $L^{-1}$ (10 h with 200-cc methanol) | ~1250 Wh $^{-1}$ | ~26 |
| Toshiba | Handheld device (1 W) | 143 Wh $L^{-1}$ (20 h with 25-cc methanol) | ~800 Wh $L^{-1}$ | ~16 |
| Samsung | Laptop computer | (100 Wh on a single fuelling) | ~1000 Wh $L^{-1}$ | ~20 |
| SFC Smart Fuel Cell | Electric vehicle | (11.1 kWh on a single fuelling) | ~1110 Wh $L^{-1}$ | ~23 |

consumer safety. The International Civil Aviation Organization and the US Department of Transportation had been allowed DMFC and its cartridge to bring in the airplane but the methanol refill tank was still forbidden [74]. Better handling of methanol cartridge is important before it was release as commercialisation product.

Passive delivery system was clearly different from the active system including the MEA structure. New structures were developed to enhance liquid/gas transport, methanol crossover, impedance, low costing, volume and weight. It was due to passive DMFC that majorly used for portable applications that require lower current densities than active system. Hence, simpler MEA for passive DMFC was required. Conventional structure with titanium mesh by Shao et al. [75] and N-DMFC by Zheng et al. [76] was developed to established new perspective of MEA passive DMFC. Those new structures facilitated better methanol transportation and $CO_2$ removal.

Methanol barrier layers were used to reduce methanol crossover in passive DMFC. Some materials had been used as barrier layer were hydrogels, Nafion membranes, porous PTFE plates and micro channels [61]. Tsujiguchi et al. [77] and Abdeelkareem et al. [78] also suggested porous carbon plate (PCP) for passive DMFC to apply in between MEA and fuel reservoir to improve mass transport, water management and $CO_2$ removal. Cell orientations, current density operations, head pressure of methanol, methanol concentration were studied on effect of PCP towards passive DMFC. Besides pore diameter and thickness of PCP play significant role to enhance the performance passive DMFC. Tsujiguchi et al. also developed multi-stack with large storage for passive DMFC based on that concept. Although many researchers had put afford in improving the methanol crossover phenomena, but still further research is needed to improve the situation before commercialisation of DMFC. Finally Table 3 summarizes the advantages and disadvantages of the several flow fields design in DMFC system.

## 7. Conclusion

Direct methanol fuel cells (DMFCs) were promising candidates as power sources for portable electronic devices because of their high power density and efficient and environmentally friendly operations. The advantages of flow design were primary factors in determining the performance of the fuel distribution. Both passive and active systems were thoroughly discussed in this paper. Some approaches had been highlighted such as micro-fluidic systems, natural circulation systems and piezoelectric valve-less micropump devices. In general, active systems require an external component such as a pump, valve, or concentration controller to deliver the fluid to the system, but these components were not required for the passive system. Passive systems directly used three main mechanisms: capillaries, gravity and concentration gradients or osmosis. The development of fuel storage or management is a part of technical issues for application and commercialisation of DMFC. This issue relates to the performance as well as the market viability of DMDC compared to other power systems.

## Acknowledgements

The authors acknowledge the financial support provided by Universiti Kebangsaan Malaysia through Research University Grants UKM-GUP-2011-074 and UKM-DIP-2012-04.

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